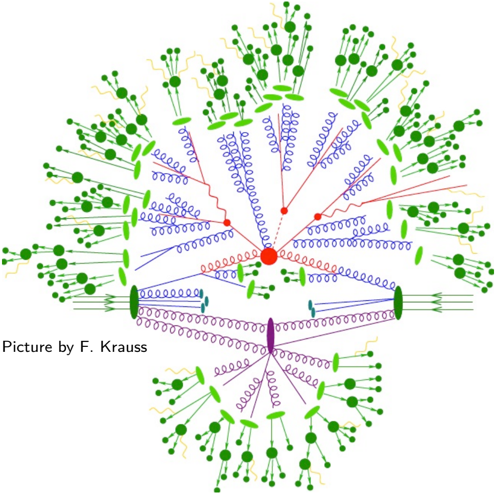
Monte Carlo tools for LHC phenomenology

Out of the Higgs Era into the Dark, IPPP

November 23, 2017

Stefan Prestel (Fermilab)



Picture by F. Krauss

Experiments to learn from:

High & low-energy DIS, $\ell\ell + hh$ *collider measurements, cosmic rays, heavy-ion collisions...*

Theory toolbox:

Hard interaction
→ Radiative cascade
→ Secondary interactions
→ Hadron formation
→ Hadron decay, rescattering, Bose-Einstein effects...

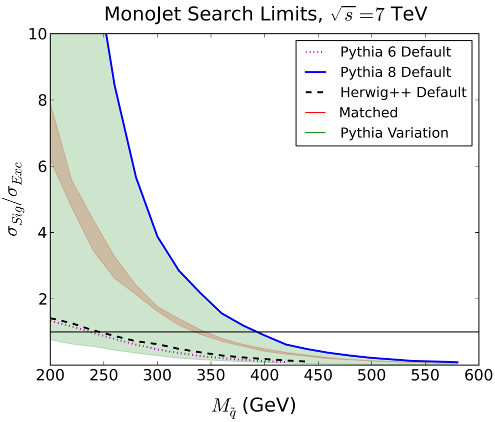
Monte Carlo Event Generators implement all these aspects.

HERWIG	PYTHIA	SHERPA
$\ell\ell$, ℓh, hh	$\ell\ell$, ℓh, hh, $\gamma\gamma$, $\chi\chi$	$\ell\ell$, ℓh, hh, $\gamma\gamma$
Some internal MEs, UFO interface, rest via LHEF	Some internal MEs, rest via LHEF	General internal MEs + UFO + general ALOHA
QCD & QED showers	QCD, QED, EW & hidden valley showers	QCD & QED showers
NLO QCD merged	NLO QCD merged	NLO QCD+aEW merged
Cluster hadronization, R-hadrons	String hadronization, R- and HV hadrons	Cluster hadronization

+ interfaces with a lot of friends, helpers and specialized tools.

Should I care about MCEG developments?

PRD87 (2013) 3, 035006 (Dreiner, Krämer, Tattersall)



Exclusion limits for squarks+jets. PS bands are obtained by varying between "wimpy" and "power shower", merged bands by varying the merging scale from $50 - 200$ GeV.

⇒ Improved QCD pins down jet momenta ⇒ More robust limits.

The Standard Model backgrounds & phase space

What are the dominant effects in which part of phase space?

Fundamental assumption: Factorisation

Long-distance and short-distance physics factorize.
(low-energy) *(high-energy)* *(we hope)*

$$\sigma = \int d\sigma_{(ab\to X+N \text{ partons})}(\text{high energy}) \otimes f_{a\in \mathrm{A}}(\{x\}_a, \text{high energy}) \otimes f_{b\in \mathrm{B}}(\{x\}_b, \text{high energy}) \otimes \mathcal{D}(p_A, p_B, p_1, \ldots, p_N) + \mathit{corrections}$$

- ◇ Extract/fit f and $\mathcal{D}$ where corrections are small (low energy).
- ◇ Use perturbation theory to calculate $d\sigma$ at high energy.
  Make accurate (NLO, NNLO) to capture most of the dynamics.
  Hope: Less impact of non-perturbative modelling.

Making fixed-order calculations practical

NLO prediction of observable $\mathcal{O}$:

$$\langle\mathcal{O}\rangle^{\text{NLO}} = \int \mathrm{B}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{V}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{R}\ d\Phi_{+1}\ \mathcal{O}(\Phi_{+1})$$

Making fixed-order calculations practical

NLO prediction of observable $\mathcal{O}$:

$$\langle\mathcal{O}\rangle^{\text{NLO}} = \int \mathrm{B}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{V}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{R}\ d\Phi_{+1}\ \mathcal{O}(\Phi_{+1})$$

Remove poles for numerical integration ⇒ Subtract & add counterterm

$$\langle\mathcal{O}\rangle^{\text{NLO}} = \int \left[\mathrm{B} + \mathrm{V} + \int \mathrm{BS}\right] d\Phi\ \mathcal{O}(\Phi) + \int \left[\mathrm{R}\ \mathcal{O}(\Phi_{+1}) - \mathrm{BS}\ \mathcal{O}(\Phi')\right] d\Phi_{+1}$$

Making fixed-order calculations practical

NLO prediction of observable $\mathcal{O}$:

$$\langle\mathcal{O}\rangle^{\text{NLO}} = \int \mathrm{B}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{V}\ d\Phi\ \mathcal{O}(\Phi) + \int \mathrm{R}\ d\Phi_{+1}\ \mathcal{O}(\Phi_{+1})$$

Remove poles for numerical integration ⇒ Subtract & add counterterm

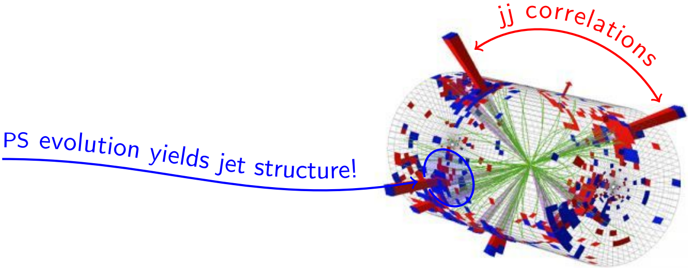
$$\langle\mathcal{O}\rangle^{\text{NLO}} = \int \left[\mathrm{B} + \mathrm{V} + \int \mathrm{BS}\right] d\Phi\ \mathcal{O}(\Phi) + \int \left[\mathrm{R}\ \mathcal{O}(\Phi_{+1}) - \mathrm{BS}\ \mathcal{O}(\Phi')\right] d\Phi_{+1}$$

Still can't generate events! ⇒ Add/subtract more & shift the blame!

$$\begin{aligned}\langle\mathcal{O}\rangle^{\text{NLO}} = & \int \left[\mathrm{B} + \mathrm{V} + \int \mathrm{BS} + \left(\int \mathrm{BP} - \int \mathrm{BS}\right)\right] d\Phi\ \mathcal{O}(\Phi) \\ + & \int [\mathrm{R} - \mathrm{BP}]\ \mathcal{O}(\Phi_{+1}) d\Phi_{+1} + \int \mathrm{BP}\left[\mathcal{O}(\Phi_{+1}) - \mathcal{O}(\Phi)\right]\ d\Phi_{+1}\end{aligned}$$

Problem is now in the final purple remainder.
The simplest way to generate this is with a parton shower!

Parton shower evolution



Parton shower (PS) evolves high energy fixed-order cross section to low energy, summing large logarithmic perturbative corrections

...by generating an arbitrary number of (soft/collinear) emissions.
...and corresponding soft/collinear virtual corrections (Sudakov factors).

Finiteness is guaranteed by *parton shower unitarity* of emission/no-emission probabilities.

Shower & matching/merging crash course

Probability of no emission (Π) = 1 - probability for an emission

$$\textbf{PS}\,[\mathrm{B}] = \underbrace{\mathrm{B}\Pi_0\mathcal{O}_0}_{\textbf{no emission}} + \underbrace{\int_1 \mathrm{B}\,P\Pi_0\left[\Pi_1\mathcal{O}_1+\dots\right]}_{\textbf{at least 1 emission}} \tag{1}$$

$$\equiv \mathrm{B}\mathcal{O}_0 - \int_1 \mathrm{B}\,P\mathcal{O}_0\Pi_0 + \int_1 \mathrm{B}\,P\;\Pi_0\left[\Pi_1\mathcal{O}_1+\dots\right] \tag{2}$$

(3)

Shower & matching/merging crash course

Probability of no emission (Π) $=$ 1 - probability for an emission

$$\begin{aligned}
\textbf{PS}\,[\mathrm{B}] \;&=\; \underset{\textbf{no emission}}{\mathrm{B}\Pi_0\mathcal{O}_0} \;+\; \int_1 \underset{\textbf{at least 1 emission}}{\mathrm{B}P\Pi_0\left[\Pi_1\mathcal{O}_1 + \ldots\right]} && (1)\\
&\equiv\; \mathrm{B}\mathcal{O}_0 \;-\; \int_1 \mathrm{B}P\mathcal{O}_0\Pi_0 \;+\; \int_1 \mathrm{B}P\;\Pi_0\left[\Pi_1\mathcal{O}_1 + \ldots\right] && (2)\\
&=\; \mathrm{B}\mathcal{O}_0 \;-\; \int_1 \mathrm{B}P\mathcal{O}_0\Pi_0 \;+\; \int_1 \mathrm{B}P\Pi_0\mathcal{O}_1 \;-\; \int_2 \mathrm{B}PP\Pi_0\Pi_1\mathcal{O}_1 \\
&\quad\;+\; \int_2 \mathrm{B}PP\Pi_0\Pi_1\left[\Pi_2\mathcal{O}_2 + \ldots\right] && (3)
\end{aligned}$$

Shower & matching/merging crash course

Probability of no emission $(\Pi) = 1$ - probability for an emission

$$\textbf{PS}\,[\mathrm{B}] = \underset{\textbf{no emission}}{\mathrm{B}\Pi_0\mathcal{O}_0} + \int_1 \underset{\textbf{at least 1 emission}}{\mathrm{B}P\Pi_0\left[\Pi_1\mathcal{O}_1 + \ldots\right]} \tag{1}$$

$$\equiv \mathrm{B}\mathcal{O}_0 - \int_1 \mathrm{B}P\mathcal{O}_0\Pi_0 + \int_1 \mathrm{B}P\,\Pi_0\left[\Pi_1\mathcal{O}_1 + \ldots\right] \tag{2}$$

$$= \mathrm{B}\mathcal{O}_0 - \int_1 \mathrm{B}P\mathcal{O}_0\Pi_0 + \int_1 \mathrm{B}P\Pi_0\mathcal{O}_1 - \int_2 \mathrm{B}PP\Pi_0\Pi_1\mathcal{O}_1 + \int_2 \mathrm{B}PP\Pi_0\Pi_1\left[\Pi_2\mathcal{O}_2 + \ldots\right] \tag{3}$$

(2) $+\,\mathcal{O}(\alpha_s)$ corrections $\mathrm{B} \to \mathrm{B}_0^{NLO}$: NLO+PS matching.

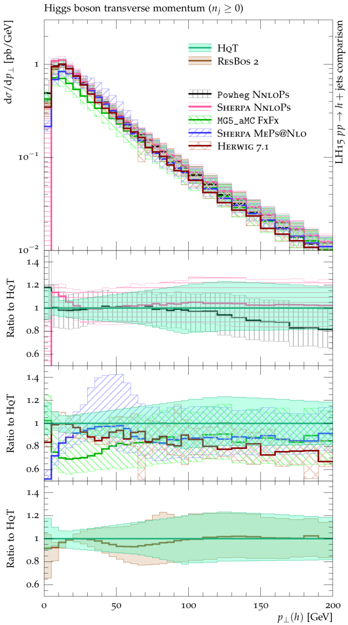
(3) with substitutions $\mathrm{B}P \to \mathrm{B}_1$ and $\mathrm{B}PP \to \mathrm{B}_2$: LO merging.

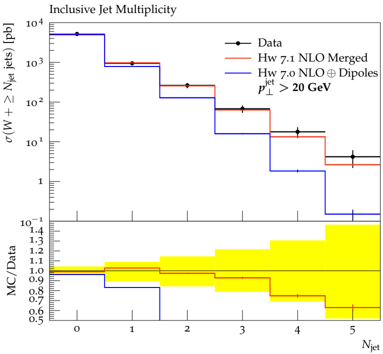
(3) with $\mathrm{B} \to \mathrm{B}_0^{NLO}$, $\mathrm{B}P \to \mathrm{B}_1^{NLO}$ $+$ subtractions: NLO merging.

The devil's in the details: Many ways to implement ⇒ many schemes!

Hiding behind the Higgs?

Plots from arXiv:1605.04692 & Herwig7 (supplied by J. Bellm)





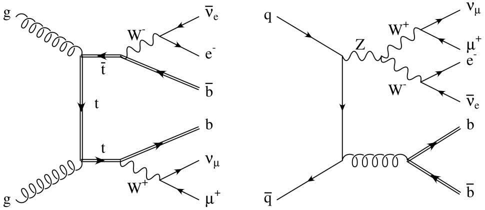
Multijet data requires multijet QCD. Records: NLO merging and NNLO matching.

But plenty of room to hide behind the SM uncertainties!

Matching complicated processes: Resonances & matching

JHEP1512(2015)065, JHEP1606(2016)027, arXiv:1607.04538

Higher orders very different for different "production processes".



"Kinematic edges" very sensitive to effects beyond NWA and to higher orders – but very useful for observables.

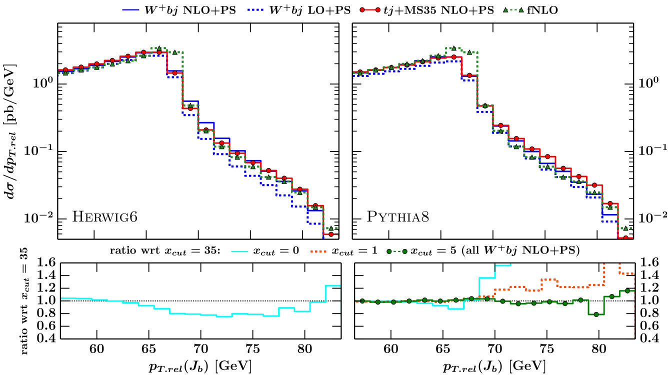
Problems to tackle:

Better control over non-resonant & non-factorizable corrections (worry about soft gluons with $E_{real\ gluon} \sim \Gamma$).

Better control over hard radiation in production & decay.

Matching Wbj with aMC@NLO

arXiv:1603.01178



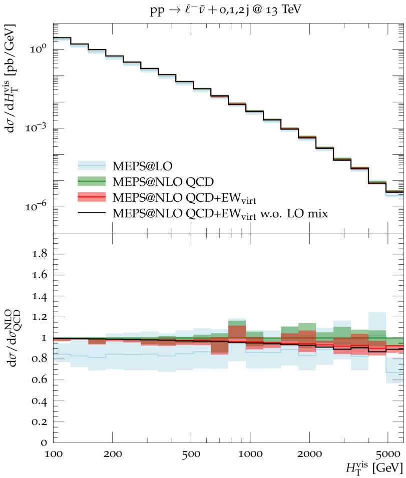
Dependence on resonance treatment parametrized with $xcut$.

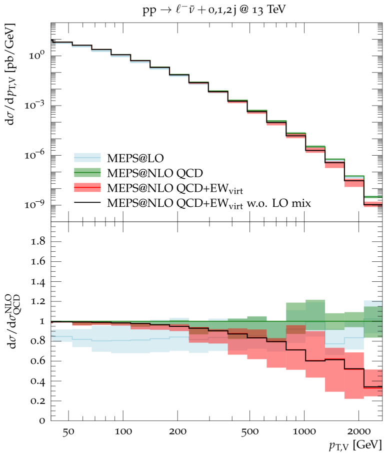
Edge depends on details of resonance treatment and parton shower.

$\Rightarrow$ Be careful if your favorite model hides below SM edges!

Towards simulating the full SM

arXiv:1511.08692





SHERPA combines NLO QCD multi-jet merging with approximate NLO EW corrections. NLO EW effects can be important.

Warnings for background simulations

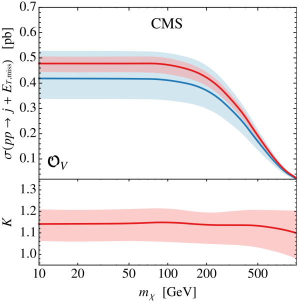
- Use multi-jet merged calculations for multi-jet backgrounds (NLO where possible)
- Stay away from SM-induced kinematic edges.
  Similarly, don't look too closely at shape of b-jets.
- When in doubt, use two different merging schemes.
- Include EW corrections for hard leptons and for $p_{\perp V}$.

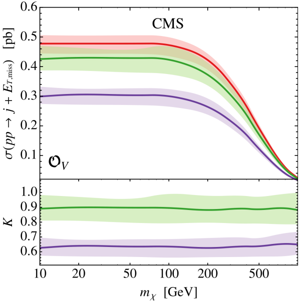
Repurposing accurate SM tools for BSM pheno

Background simulations are quite sophisticated. Can we leverage this knowledge also to improve signal extraction?

When the detector only sees QCD I: Dark matter in mono-jets

Plots from arXiv:1310.4491; Powheg-Box



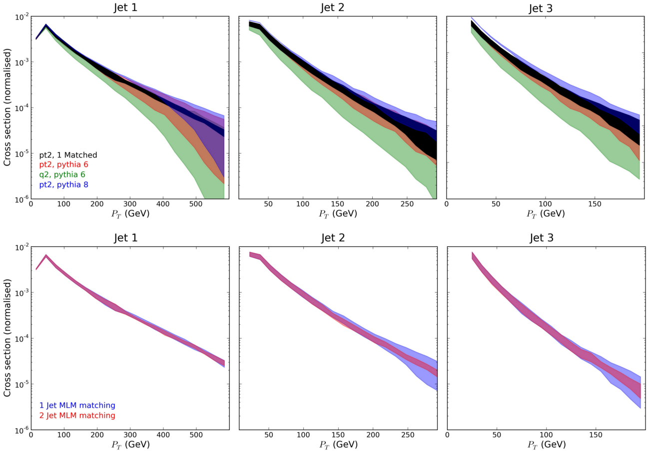


NLO corrections suggest more stringent limits, NLO+PS with realistic analysis less optimistic.

But in either case, more robust limits!

When the detector only sees QCD II: Compressed mass spectra

Plots from Phys.Rev. D87 (2013) no.3, 035006; MG5+Pythia

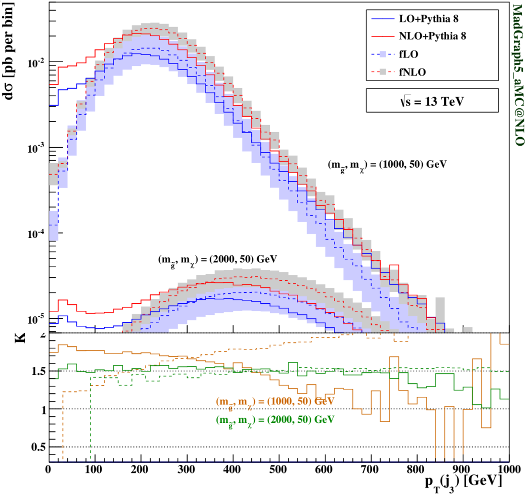


Squark pair production with compressed squark-LSP masses.

If you only see QCD, make sure to minimize uncertainties!
Most tools allow LO multi-jet merging for new-physics processes.

NLO+PS matching for BSM

Figure from arXiv:1510.00391; aMC@NLO+Pythia



NLO K-factors are not flat. ⇒ Constant rescaling of LO not ideal.

NLO+PS closer to NLO than LO+PS to LO (better control of reals)

Still work to do on treatment of resonance enhancements.

Using QCD to aid BSM searches

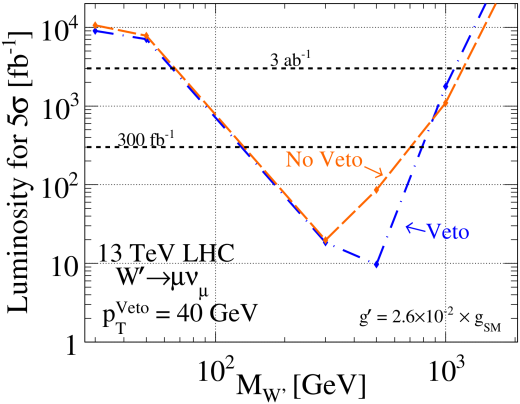
Figure from arXiv:1701.05263

QCD "knows" about typical scales of processes

…e.g. probability for extra jets slightly process-dependent.

$\Rightarrow$ Can use jet vetoes can improve "signal/noise"

…needs accurate BSM+QCD calc^n to minimize uncertainty on σ^{veto}

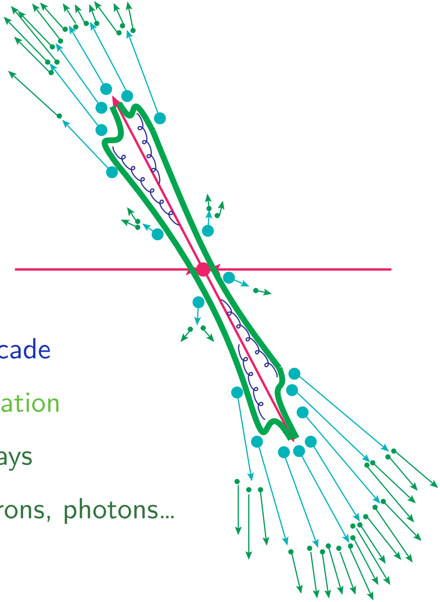


Physics beyond (fixed-order) perturbation theory

Remember:
Perturbation theory $\in$ Nature *but* Nature $>$ ME calculations

Example: What are signatures of "rich" dark sectors?

Realistic scattering events



Hard interaction

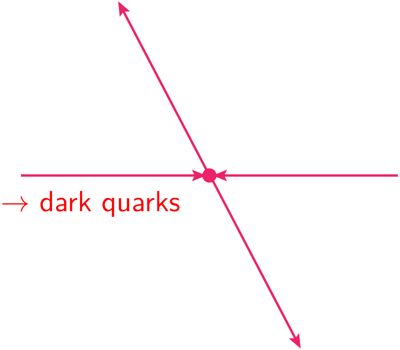
→ Radiative cascade

→ Hadron formation

→ Hadron decays

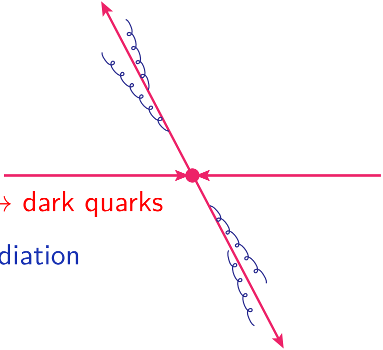
⇒ Stable hadrons, photons...

Realistic scattering events... with dark sectors



Hard interaction → dark quarks

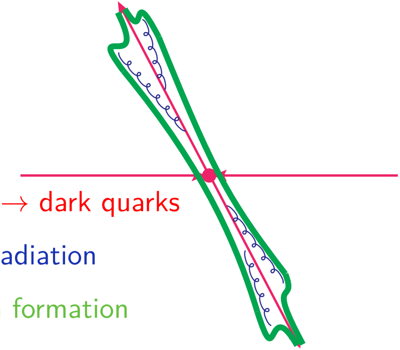
Realistic scattering events... with dark sectors



Hard interaction → dark quarks

→ Dark sector radiation

Realistic scattering events... with dark sectors

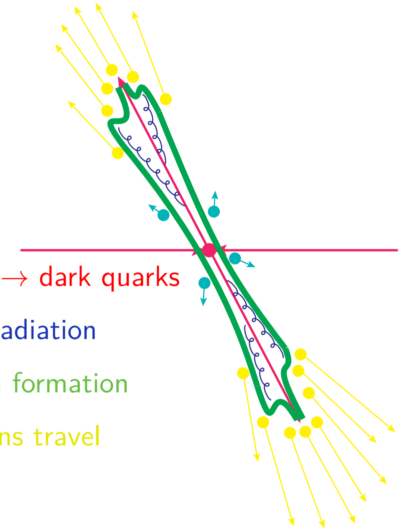


Hard interaction → dark quarks

→ Dark sector radiation

→ Dark hadron formation

Realistic scattering events... with dark sectors



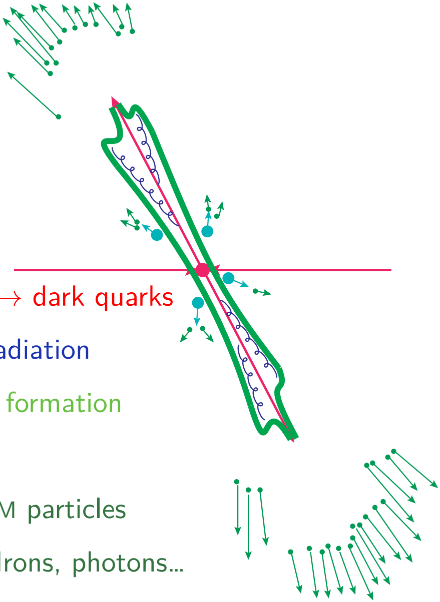
Hard interaction → dark quarks

→ Dark sector radiation

→ Dark hadron formation

→ Dark hadrons travel

Realistic scattering events... with dark sectors



Hard interaction → dark quarks

→ Dark sector radiation

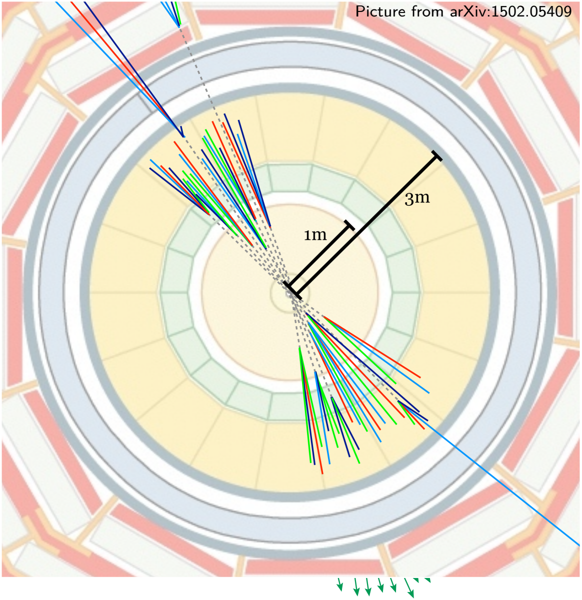
→ Dark hadron formation

→

→ Decay to SM particles

⇒ Stable hadrons, photons...

Realistic scattering events... with dark sectors



Picture from arXiv:1502.05409

Hard interacti

→ Dark secto

→ Dark had

→

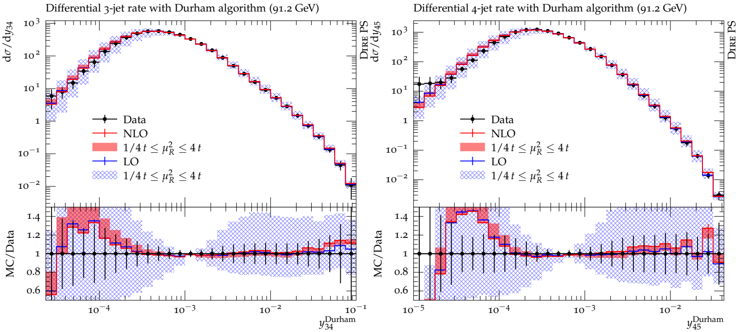
→ Decay t

⇒ Stable

Jets and the dark sector

Plot from arXiv:1705.00982

Semi-visible jets, emerging jets, lepton jets challenge search strategies & modelling of jets – which may be accurate, but not precise:



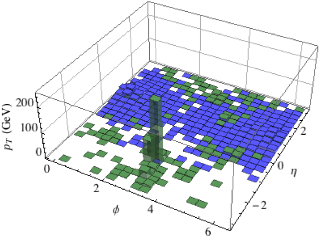
⇒ Improved showers (e.g. arXiv:1705.00742, arXiv:1611.00013) needed to prevent over-tuning non-pert. parameters & allow robust predictions?

No BSM news, really, beyond arXiv:1006.2911. Features needed?

Happily into the abyss

Soft new physics might also share features with MinBias/Pile-up.

E.g. high-multiplicity decays from dark sectors (soft bombs) might produce long-range correlations



Picture from arXiv:1612.00850

…that almost look like the unexpected "ridges" in CMS pp data.

MC news: New ideas in heavy-ion physics (arXiv:1710.09725), diffraction (arXiv:1612.04701), hadronization (arXiv:1610.09818)

Summary

- MCEGs use detailed models all apsects of scattering events. Without continuously improving their SM parts, we would have wrongly discovered new physics many times.
- Improving perturbative calc^{ns} in MCEGs has much attention, and produced very precise tools
- Many background methods can be reused for more sophisticated searches for BSM signals.
- Light or strongly coupled new physics can have interesting new signatures beyond fixed-order perturbation theory, and will push the boundaries of background calculations.